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GB 986572
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(54) Well Logging Methods and Apparatus

(57) A dual resistivity and induction apparatus for the investigation of earth formations traversed by a borehole, comprises an electrode system, supported on a support member, comprising a central electrode A_0 and five pairs of electrodes M_1, M'_1; M_2 M'_2; M_3 M'_3; A_1 A'_1; A_2 A'_2 respectively short-circuited and aligned symmetrically about the central electrode A_0 at increasing distances therefrom. A source of alternating current at a first frequency, f_1, is coupled between electrodes A_1 A'_1 and A_2 A'_2 a source of alternating current at a second frequency, f_2, is coupled between electrodes A_2 A'_2 and electrode 8 at electrical infinity with respect to the electrode system. A circuit arrangement 15 coupled to electrodes A_1 A'_1 for generating current at f_1 from electrode A_0 for maintaining the potential difference between electrode pairs M_1 M'_1 and M_2 M'_2 at substantially zero and for generating current at f_2 from electrode A_0 for maintaining the potential difference between electrode pairs M_1 M'_1 and M_3 M'_3 at substantially zero. First and second impedances are respectively interposed between each of the sources of alternating current f_1 f_2 and the current generating circuit and the electrodes A_1 A'_1. The length, along the axis of the support member, of each of the electrodes A_2 A'_2 is several orders of magnitude smaller than the relative spacing along the support member of that pair of electrodes to reduce the interference between the electrode system and the coil system R_1 R_2 R_3 and T_1 T_2 T_3 of the conventional induction log operating at a third frequency.

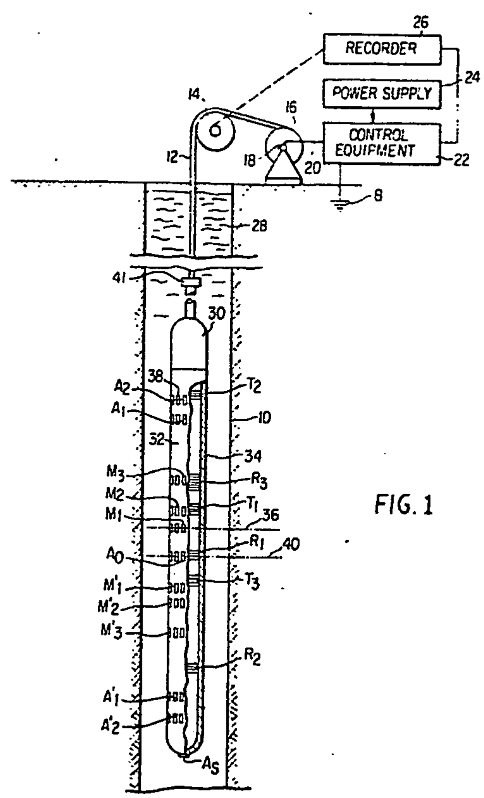
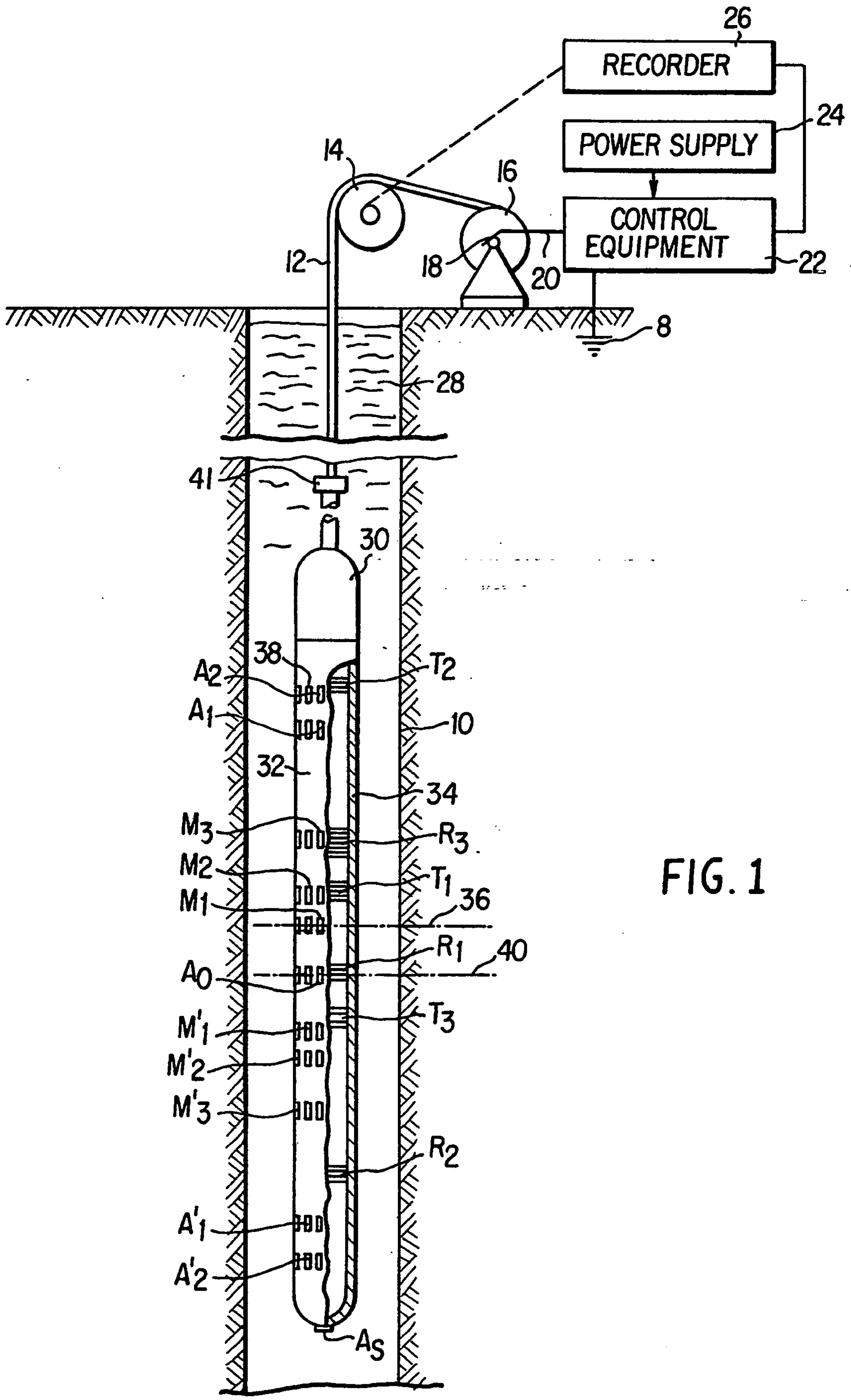


FIG. 1


RECORDER
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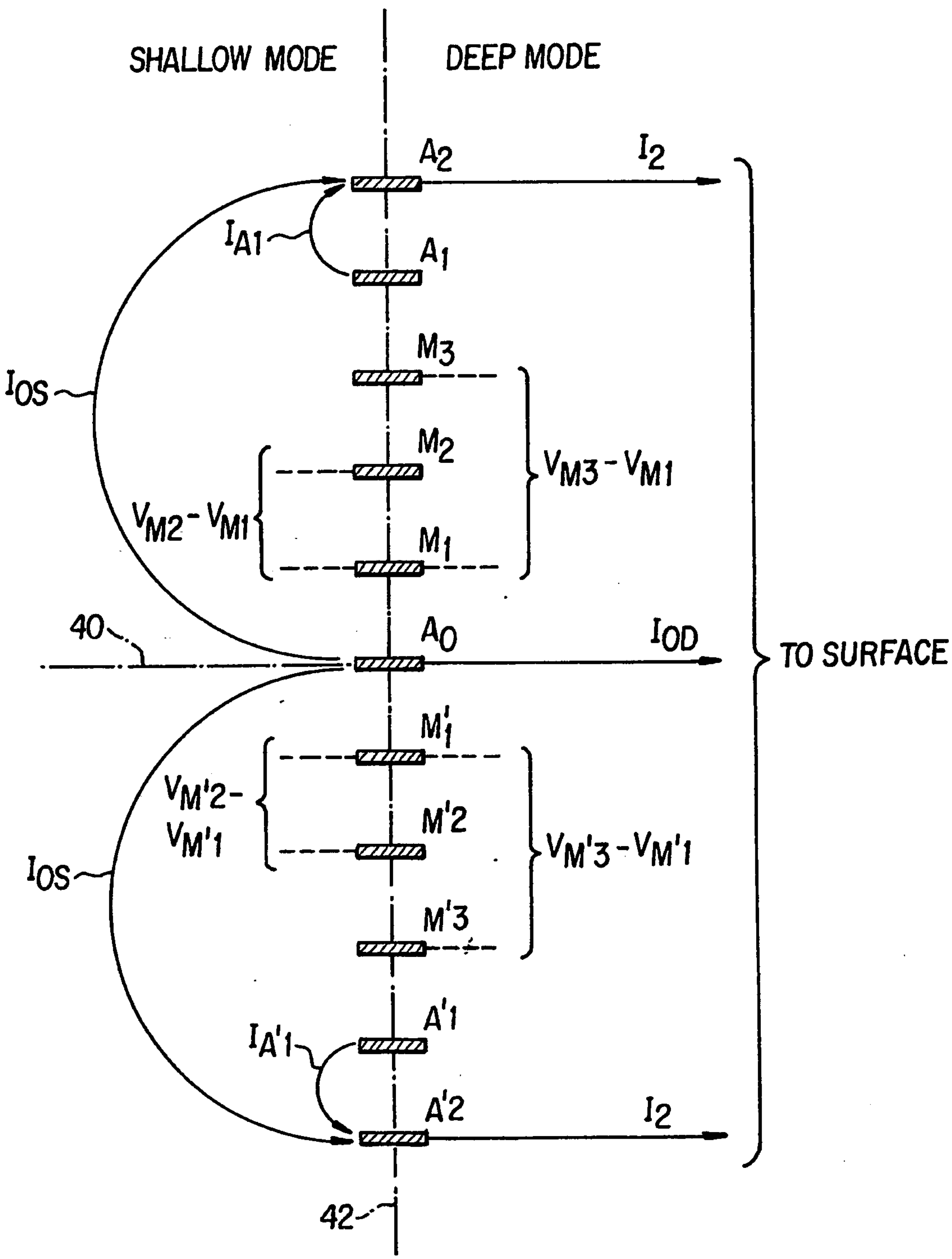
POWER SUPPLY
24
CONTROL EQUIPMENT
22
14
16
18
20
12
8
28
41
30
38
A2
A1
32
T2
10
34
M3
M2
M1
R3
T1
36
R1
40
A0
T3
M'1
M'2
M'3
R2
A'1
A'2
AS

FIG. 1



SHALLOW MODE
DEEP MODE
A2
I2
IA1
A1
M3
IOS
M2
VM3 - VM1
VM2 - VM1
M1
40
A0
IOD
TO SURFACE
M'1
VM'2-
VM'1
M'2
VM'3 - VM'1
IOS
M'3
A'1
IA'1
A'2
I2
42

FIG.2

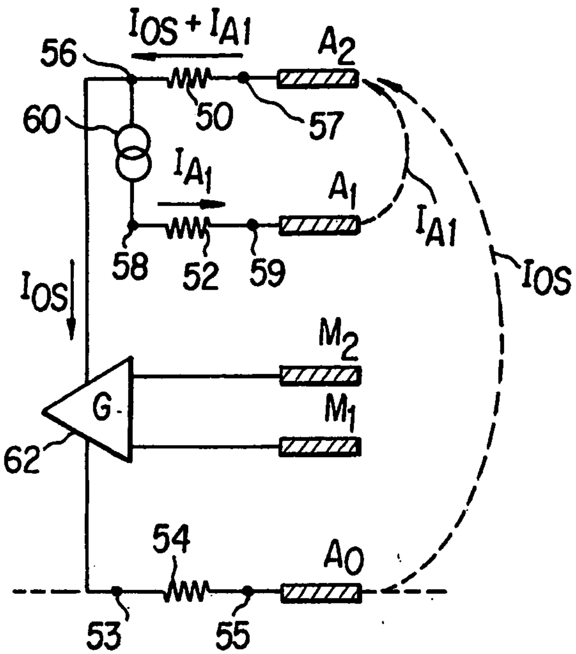


FIG. 3A

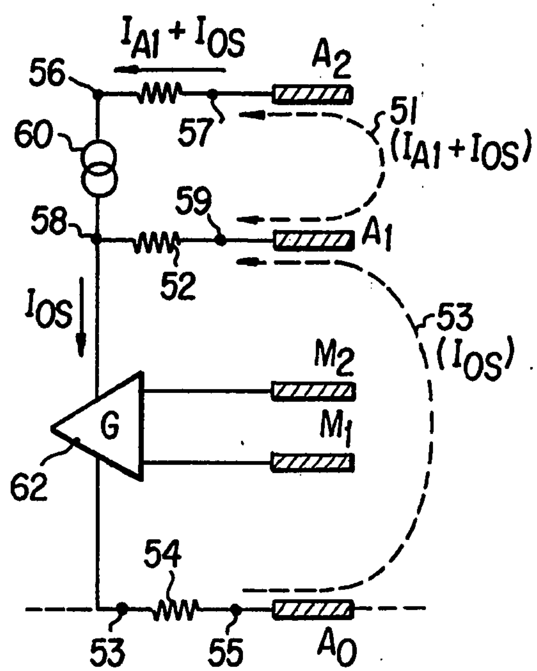


FIG. 3B

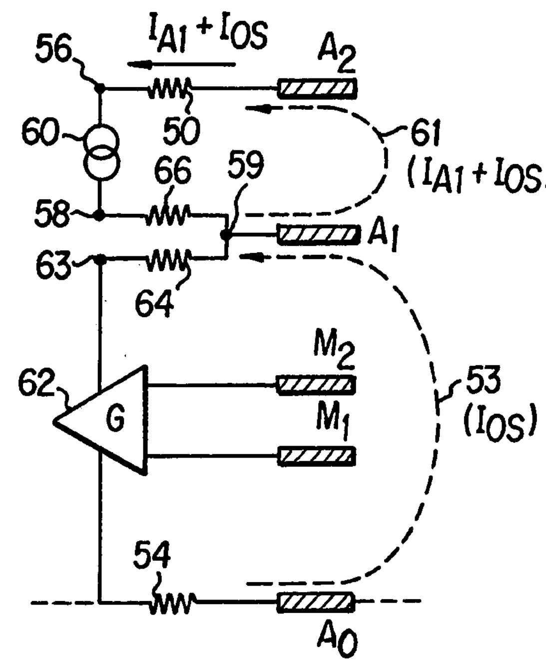


FIG. 3C

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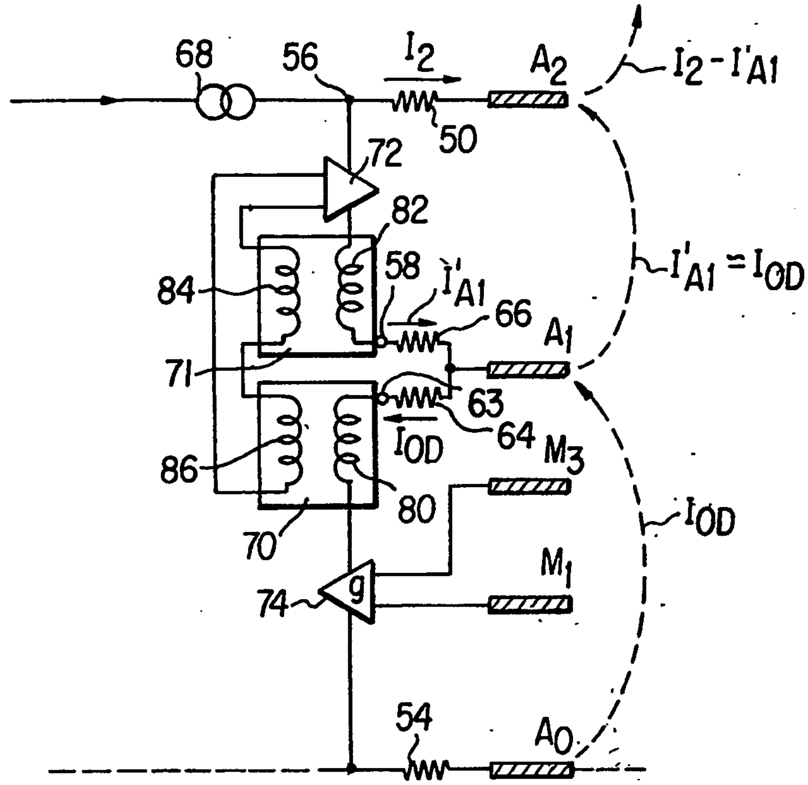

68
56
I_2
A_2
$I_2 - I'_{A1}$
50
72
82
84
58
I'_{A1}
66
A_1
$I'_{A1} = I_{OD}$
71
63
I_{OD}
64
M_3
86
80
70
I_{OD}
g
M_1
74
54
A_0

FIG. 4

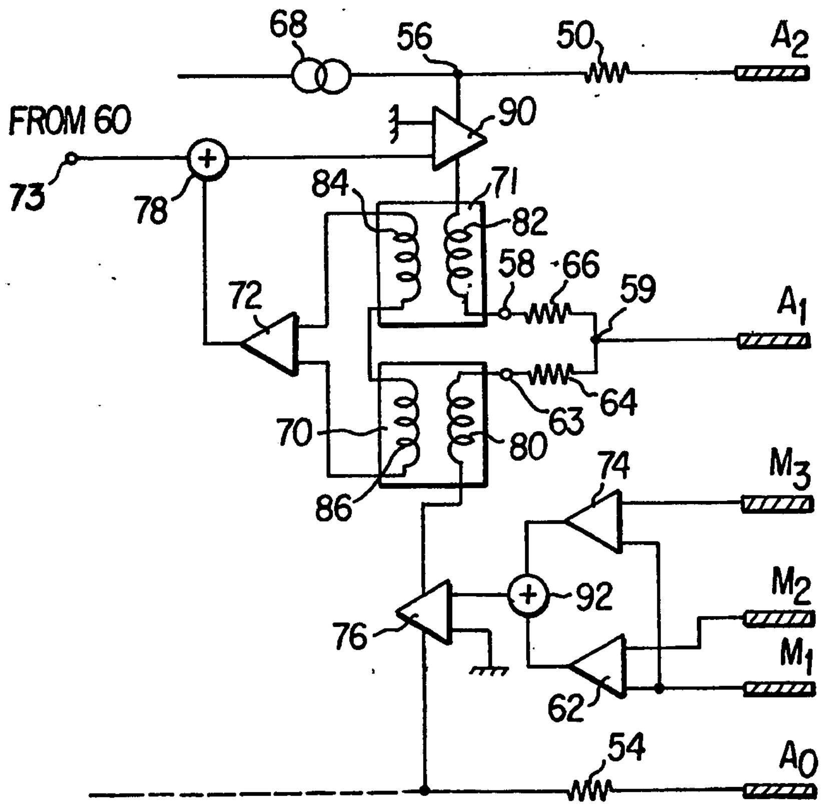
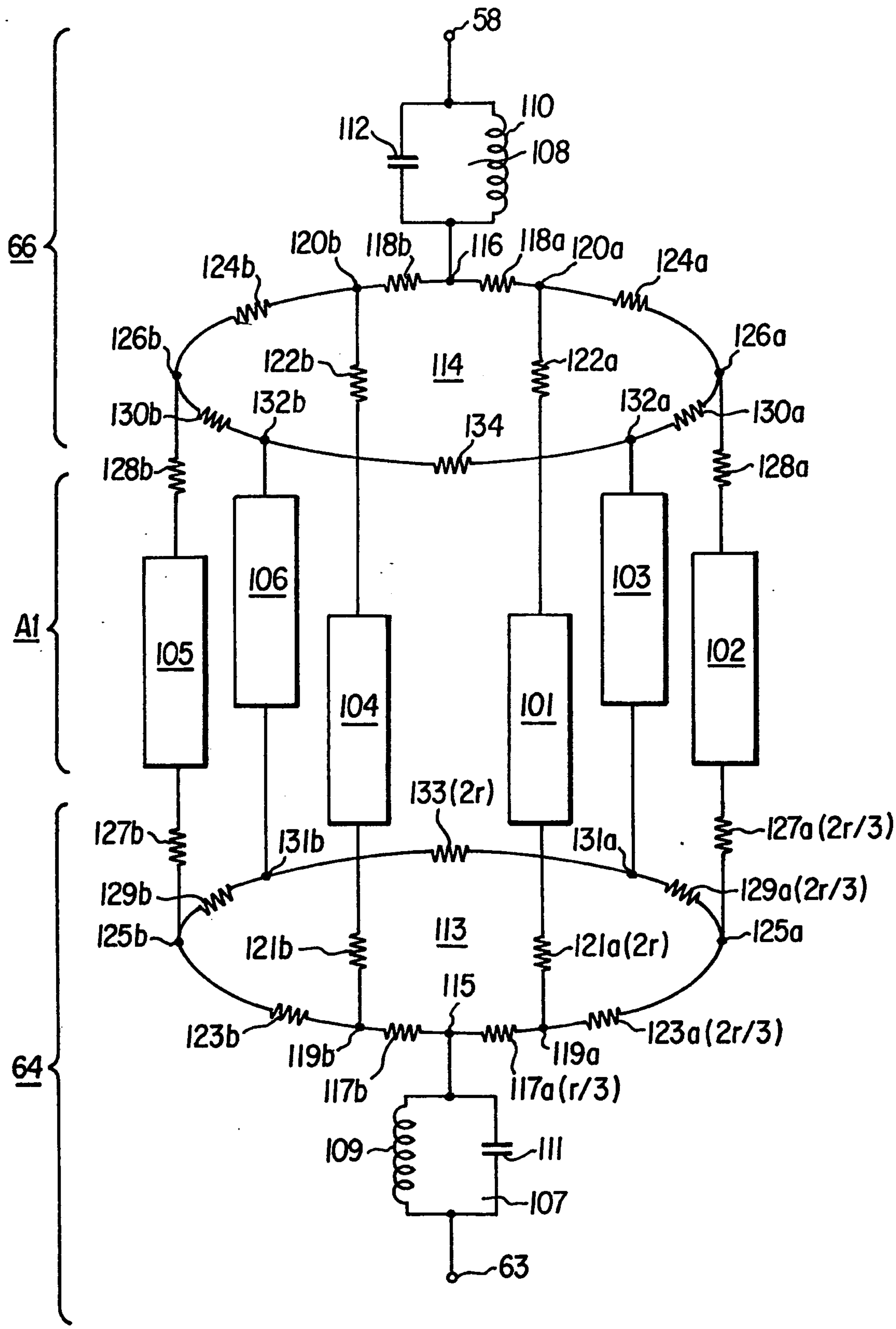

68
56
50
A_2
FROM 60
90
73
78
84
71
82
58
66
59
A_1
72
63
64
70
80
86
74
M_3
92
M_2
76
M_1
62
54
A_0

FIG. 5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110
112
108
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124b
120b
118b
116
118a
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126b
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122a
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132b
134
132a
130a
128b
128a
A1
105
106
104
101
103
102
133(2r)
127b
127a (2r/3)
131b
131a
129b
129a (2r/3)
125b
113
125a
121b
121a (2r)
115
123b
123a (2r/3)
119b
119a
64
117b
117a (r/3)
109
111
107
63

FIG. 6

SPECIFICATION

Well Logging Methods and Apparatus

The present invention relates in general to electrical well logging, and pertains in particular to improved method and apparatus for simultaneously investigating underground formation zones which are near and far from a borehole that traverses the formation zones which method and apparatus are compatible for use along with induction logging method and apparatus.

It has been the practice to investigate earth formations surrounding a borehole by lowering a sonde in the borehole so as to measure characteristics of the traversed formation such as conductivity, resistivity, porosity, etc. The formation conductivity is mainly measured by generating in the formation coil-induced electromagnetic currents and thereafter detecting with receiving coils magnetic fields generated by the induced currents. Such an apparatus is commonly called an induction sonde and the recording of the measurements versus depth is called an induction log. Reference may be had to U.S. Patent No. 2,582,314 granted to Henri G. Doll on January 15, 1952, and assigned to the Schlumberger Technology Corp. for a description of such an apparatus.

Likewise it is known that formation resistivity measurements are obtained by passing survey electrical currents through the formation via electrodes and measuring voltages between certain of the electrodes. In order to minimize the influence of the borehole and those portions of the formation which are close to the wall of the borehole, the survey current is focused into the formations by means of special electrodes to provide a mode of operation known as deep investigation as opposed to unfocused shallow investigation. Such a focusing electrode logging tool has been described in U.S. Patent No. 2,712,627 granted to H. G. Doll on July 5, 1955 and assigned to the Schlumberger Technology Corp.

It is well known that there are domains of resistivity in which induction measurements are better suited than resistivity measurements and vice versa. For example, when the ratio R_t/R_m is much greater than 1, such as in salty muds and/or in highly resistive formations, resistivity measurements are preferred; R_m commonly designates the resistivity of drilling mud in the borehole, R_{xo} the resistivity of the formation zone directly adjacent to the borehole and invaded by mud filtrate, and R_t the resistivity of the uninvaded formation zone. On the contrary, when R_t is smaller than R_m or R_{xo}, induction measurements are more satisfactory. Therefore, it has been suggested to combine on one sonde the focusing-electrode system of a resistivity sonde with a coil system of a conductivity or induction sonde. Such a system has been described in U.S. Patent No. 3,124,742 granted to William P. Schneider on March 10, 1964 and assigned to the Schlumberger Technology Corp. This patent describes a "resistivity-induction tool" allowing for the simultaneous recording of a resistivity log and an induction log on the same trip of the sonde through a well bore.

The main difficulty encountered in mounting together, in an interlaced manner, an electrode system and a coil system, arises from the sensitivity of the responses of the coils to the presence of conductive electrodes in close proximity therewith. Consequently, the number of electrodes of the sonde described in the Schneider patent, although fairly large, is minimized, and electrodes having large surfaces have been avoided. More precisely, the focusing-electrode system of the Schneider patent comprises a central current electrode A_0, two pairs of monitoring electrodes M_1—M'_1 and M_2—M'_2, one pair of auxiliary current electrodes A_1—A'_1 and one current return electrode B located on the sonde. The depth of investigation of such a system is shallow, due on the one hand to the small surface size and short spacing of the electrodes, and on the other hand to the location of the current return electrode B on the sonde. This arrangement presents a serious drawback since only a shallow investigation is possible whereas a deep investigation is often additionally required, especially when R_t and R_{xo} are substantially different.

Relatively deep and shallow depths of investigation can be simultaneously obtained with a known type of dual focusing-electrode system, called "Dual resistivity" and described in U.S. Patent No. 2,712,630 granted to Henri G. Doll on July 5, 1955, and in U.S. Patent No. 3,772,589 granted to Andre Scholberg on November 13, 1973 (the two patents are assigned to the Schlumberger Technology Corp.). The dual resistivity system operates at two different frequencies f_1 and f_2 and comprises two current return electrodes, one on the sonde for the shallow investigation and one at the surface for the deep investigation. Besides, as shown in the Scholberg patent, the current return electrodes of the shallow investigation electrode system A_2—A'_2 are used as auxiliary current electrodes for the deep investigation electrode system. These electrodes, however, are of a larger size, in order to increase the depth of investigation, and therefore cannot be used in a combined dual resistivity-induction sonde without introducing large adverse effects into the operation of the coil system.

Additionally, it is the current practice to record along with the resistivity measurements the difference between the potential of an electrode in the borehole and a fixed potential of a surface electrode, commonly known as "spontaneous potential". Large size metallic electrodes employed for the deep investigation give rise to erroneous measurements of the spontaneous potential.

It is an object of the present invention to provide a new logging method and a new electrode array for independent use or for use in

combination with a coil system of a logging sonde, which simultaneously enable deep and shallow investigation of formations surrounding a borehole. It is a further object of the present invention to provide a novel electrode array that does not disturb the simultaneous recording of a spontaneous potential measurement. The total length of the novel electrode array is configured to be sufficiently short so that a sonde equipped with such an array can easily be handled thus enhancing the ability of mounting such an array on the support member of a common induction sonde.

Yet another object of the present invention is the provision of a logging sonde comprising a novel electrode system fixed on the support member of an induction sonde in close proximity to the coils of the induction sonde. This combined system, enables the simultaneous recording of a conductivity curve and two resistivity curves at different depths of investigation of the formation within the same horizontal layer of the formation.

In accordance with a first embodiment of the present invention, a well-logging method for measuring the electrical resistivity of two underground formation zones respectively near and far from a borehole, comprises the following steps:

—applying at a first location of the borehole and receiving at two second locations of the borehole symmetrically situated on both sides of the first location, a first measurement current at a first frequency,

—applying at two third locations of the borehole symmetrically situated on both sides of the first location, between the second locations, and receiving at the second locations, a first focusing current at the first frequency,

—varying the amplitude of the first measurement current so as to minimize the potential difference existing at the first frequency between respective ones of two fourth and two fifth locations of the borehole symmetrically situated in respective order on both sides of the first location, between the two third locations,

—deriving from the amplitude of the first measurement current and the potential difference existing at the first frequency between the two fourth locations and a sixth location which is remote from the aforementioned first through fifth locations a measure of the resistivity of a formation zone near the borehole,

—applying at the first location and receiving at a seventh location on the surface, a second measurement current at a second frequency,

—applying at the second locations and receiving at the seventh location a second focusing current at the second frequency,

—varying the amplitude of the second measurement current so as to minimize the potential difference existing at the second frequency between respective ones of the two fourth locations and two eighth locations respectively situated symmetrically on both sides of said first location between the third and fourth locations, and

—deriving from the amplitude of the second measurement current and the potential difference existing at the second frequency between the fourth locations and the sixth location a measure of the resistivity of a formation zone far from the borehole, wherein

—the two second locations have a dimension along the borehole axis which is small relative to their spacing distance,

—the eighth locations are placed midway between the third and fifth locations, and

—the amplitude of the second measurement current detected at the third locations is minimized.

The well-logging method according to the present invention makes it possible to achieve a double result. First of all, one obtains, with a very good vertical resolution, a good measurement of the resistivity of the formation zones near the borehole as long as the contrast between the resistivity of the uninvaded formation zone and that of the mud filtrate is small (less than about one thousand) and the diameter of the borehole near the sonde does not greatly vary from its nominal diameter (factor of two maximum). Additionally, one obtains, also with a good vertical resolution, a good measurement of the resistivity of the uninvaded formation zones, as long as the mud filtrate invasion depth remains small relative to the extreme spacing of the second locations (i.e. no more than two-thirds). If this double result is compared with the one provided by the prior art method (Scholberg patent) in which the dimension along the borehole axis of the second location is comparable in length to their relative spacing, the following is noted. Firstly, in addition to the easier implementation due to the size reduction, the quality of a resistivity measurement in a formation zone near the borehole is hardly modified and, secondly, the compromise between increasing the mud filtrate invasion sensitivity of the resistivity measurement in the uninvaded zone, on the one hand, and the reduction in the vertical sensitivity of this measurement, on the other hand, is altogether acceptable.

In accordance with another embodiment of the present invention, a well-logging method following the principles described with respect to the first embodiment comprises the following additional steps:

—inducing into the formation zones electromagnetic energy at a third frequency much higher than the first and the second frequency,

—measuring the currents at the third frequency thus induced into the formation zones and deriving therefrom a value of the conductivity of these formations, and

—modifying the flow conditions of the focusing and measurement current at the first and at the second frequency by providing independent flow paths at each of said two third locations for each of said focusing currents and said measurement current.

Therefore, it becomes possible, while measuring the conductivity of the formations electromagnetically, to carry out electrical measurement of the resistivity of two zones of the formation in accordance with the disclosure of the first embodiment of the present invention.

The invention will now be described, by way of example only, with reference to the accompanying drawings, of which:

Figure 1 is an elevational view of a representative embodiment of a well logging sonde comprising an induction sonde supporting an electrode system in conformity with the invention, said sonde having a portion cut away to reveal the coils of the induction system;

Figure 2 illustrates schematically the two modes of operation (shallow and deep investigation) of the new electrode array of Figure 1;

Figure 3A, 3B and 3C represent schematically one-half of the symmetrical electrode array of Figure 1, and its associated circuits for shallow investigation, Fig. 3A showing the theoretical circuit, Fig. 3B showing the measurement circuit equivalent and Fig. 3C showing the circuit of the invention;

Figure 4 represents schematically one-half of the symmetrical electrode array of Figure 1, and its associated circuit for deep investigation;

Figure 5 represents schematically one-half of the electrode array of Figure 1, with its associated circuits for simultaneous deep and shallow investigations; and

Figure 6 represents a current electrode assembly for use in the embodiment of Figure 1.

Referring to Figure 1 of the drawings, there is shown a representative embodiment of an apparatus or sonde for investigating earth formations traversed by a borehole 10. The apparatus is suspended in the borehole at the extremity of a multi-conductor cable 12, which passes over a pulley 14. The sonde can be lowered or raised in the borehole with the help of a conventional winch 16. The conductors in the cable 12 may be connected through slip rings 18 and conductors 20 to surface control equipment 22. The necessary power to operate the downhole electronic equipment may be supplied by a power supply 24 at the surface. The electrical indications obtained in the borehole may also be recorded at the surface on conventional recording means 26 connected to the control equipment 22 and mechanically driven from the pulley 14 so as to record measurements as a function of depth. The borehole 10 contains drilling mud 28.

The sonde has two main parts: an upper part comprising an electronic cartridge 30 and a lower part 32 on which a coil system and an electrode system are supported. The electronic cartridge 30 comprises electronic circuitry associated with both the coil system and the electrode system and is provided with a housing made of an electrical insulating material which is also pressure-resistant and fluid-tight.

The lower part 32 of the sonde is formed by a support member 34 made of a non-conductive and non-magnetic material, such as a plastic impregnated fiberglass. Secured to the support member is the coil system which can be one of the systems described in the Doll Patent No. 2,582,314. For example, the coil system shown in Figure 1 comprises a principal, transmitter coil T_1, an auxiliary focusing transmitter coil T_2, a receiver coil R_1 and a focusing receiver coil R_2 as well as an auxiliary compensating transmitter coil T_3 located between the receiver coils R_1 and R_2 and an auxiliary compensating receiver coil R_3 placed between the transmitter coils T_1 and T_2. The coils are secured along the length of the support member substantially symmetrical with respect to the axis 36 thereof.

The electrodes of the electrode system are each formed of a plurality of conductive strips of small surface areas which are connected together by a resistive ring. The conductive strips are in contact with the mud while the ring is embedded in an insulating material. The electrodes may be printed circuits realized on a flexible support, in plastic for example. The structure of the electrodes, fully described in the Schneider patent, has the advantage of making them more resistive to the electrical current induced by the coils than the usual electrodes formed by a single sleeve of conductive material. In order to reduce interference between the two systems, the position of the strip electrodes with regard to the position of the coils is chosen by carrying out a method described in the already mentioned Schneider patent. This method consists of investigating the response of the coil system to an elemental closed loop conductor moved along and around the coil system. The output signal of such a coil system is plotted versus the position of the loop conductor along the coil system and the position of the electrodes is selected at the locations where the output signal is minimal. The electrode array, as shown in Figure 1, is composed of a survey electrode A_0 located along axis 40 and five pairs of electrodes symmetrically located with respect thereto. A reference electrode 41 is remotely located at some twenty meters from the sonde on an isolated section of the cable 12. The first three pairs of electrodes surrounding survey electrode A are monitoring electrode pairs M_1—M'_1, M'_2—M'_2 and M_3—M'_3. The two other pairs are auxiliary current emitting electrodes A_1—A'_1 and A_2—A'_2.

For usual boreholes (diameter length between 200 and 250 mm) the diameter of the sonde is around 90 mm and the length of current electrodes is about 80 mm while the length of the voltage electrodes is smaller. For such an electrode array as shown in Figure 1, a desirable spacing has been found to be: A_0 to M_1—M'_1: 305 mm; A_0 to M_2 or M'_2: 423 mm; A_0 to M_3—M'_3: 838 mm; A_0 to A_1—A'_1: 1,219 mm and A_0 to A_2—A'_2: 1,473 mm the spacing distance between axis 40 of the electrode system and axis 36 of the coil system can be about 250 mm. It will be

appreciated that the length of the electrode array is small enough so that the electrode system can be mounted on the support member of most of the induction logging sondes presently used. Moreover, the electrode array of the present invention can be mounted on a separate mandrel and used independently of any coil system to provide a dual focusing-electrode system sonde having a relatively short length. An electrode A_s located on the bottom of sonde part 32 is provided in conjunction with surface electrode B to enable the measurement of the spontaneous potential of earth formation therebetween.

The operation of the electrode array of Figure 1, is schematically illustrated in Fig. 2. Electrodes are represented along the longitudinal axis 42 of the support member. The left and right sides of Figure 2 respectively illustrate the operation of the shallow and deep investigation modes of the electrode system. In both modes of operation, survey electrode A_0 emits simultaneous survey currents into the adjacent formation which are designated I_{OD} for the deep survey current and I_{OS} for the shallow survey current. The respective frequencies of the shallow and deep survey currents can be 280 Hz and 35 Hz. Electrodes of the same symmetrically located pair may be electrically strapped or, preferably, kept at the same potential by electronic means.

In the shallow mode of investigation, the pair of monitoring electrodes M_3 and M'_3 are not used; only monitoring pairs M_1, M'_1 and M_2, M'_2 are used. The potential difference $V_{M2}—V_{M1}$ between electrodes M_2 and M_1 is kept substantially equal to the potential difference $V_{M'2}—V_{M'1}$ between electrodes M'_2 and M'_1 by controlling the amplitude of the measure current I_{OS} emitted by the central electrode A_0 and received by the auxiliary electrodes A_2 and A'_2 respectively. Besides, as explained in the Scholberg patent, the focusing current generated between electrodes $(A_1—A'_1)$ and $(A_2—A'_2)$ is controlled such that the total electric power $(V_{M1} \cdot I_{OS})$ is kept substantially constant, the potential V_{M1} being measured with respect to the remote electrode 41.

A convenient way to monitor the measurement current I_{OS} is to have $V_{M2}—V_{M1}+V_{M'1}—V_{M'2}=0$. The value of resistivity R_S of the investigated formation adjacent the borehole, for a shallow depth of investigation, is then obtained by the following equation:

$$R_S=k_1\frac{V_{M1}+V_{M2}+V_{M'1}+V_{M'2}}{4\,I_{OS}}$$

where k_1 is a constant geometrical factor of the shallow investigation system. However, when the monitoring loop is efficient enough to keep $V_{M1}=V_{M2}$ and $V_{M'1}=V_{M'2}$, the resistivity R_S is obtained by the simplified equation:

$$R_S=k_1\frac{V_{M1}+V_{M'1}}{2\,I_{OS}}$$

this resistivity R_S is substantially that of a formation bed the thickness of which is the distance between electrodes $M_1—M'_2$. As the distance $A_0—M_1$ is substantially equivalent to the borehole diameter, the position of the tool within the borehole does not substantially affect the shallow resistivity measurement R_S.

During operation in the deep investigation mode, an auxilairy focusing current I_2 is emitted through the pair of electrodes A_2 and A'_2. Deep survey or measure current I_{OD} and auxiliary current I_2 return to the surface to be received by a surface electrode B (shown in Figure 1). The value of measure current I_{OD} is controlled so as to maintain the potential difference $V_{M3}—V_{M1}$ between electrodes M_3 and M_1 substantially equal to the potential difference $V_{M'3}—V_{M'1}$ between electrodes M'_3 and M'_1. It can be shown that, in that case, current I_2 and I_{OD} are forced to penetrate into the formation in a direction which is substantially perpendicular to the longitudinal axis of the logging sonde and therefore, when the sonde is not tilted in the borehole, perpendicular to the longitudinal axis of the borehole. As a consequence, the depth of investigation is larger than that obtained during operation in the shallow investigation mode. Actually the measured deep resistivity R_D is close to the resistivity R_t of the non-invaded zone as long as the invasion depth is about twice shorter than the span between electrodes A_2, A'_2. This condition is obtained in about 80% of the cases. For the deep investigation system, the total current (at 35 Hz) circulating between the remote return electrode and the sonde current electrodes is controlled by means of a feed-back loop in order to keep constant the total electric power at that frequency applied to the formations.

A practical way to implement the monitoring of the measurement current I_{OD} is to have $V_{M3}—V_{M1}+V_{M'1}—V_{M'3}=0$. The resistivity R_D of the formations surrounding the borehole, for a deep investigation mode of operation, is given by the following equation:

$$R_D=k_2\frac{V_{M1}+V_{M3}+V_{M'1}+V_{M'3}}{4I_{OD}}$$

where k_2 is a constant geometrical factor of the deep investigation system.

When the monitoring loop is efficient and fast enough to keep $V_{M1}=V_{M3}$ and $V_{M'1}=V_{M'3}$, the value R_D is obtained by the simplified equation:

$$R_D=\frac{k_2(V_{M1}+V_{M'1})}{2I_{OD}}$$

This resistivity R_D is substantially that of a formation bed the thickness of which is the distance between electrodes $M_1—M'_3$.

Figure 3A represents, schematically, one-half of the shallow electrode array of Fig. 1, and its associated circuit. Electrodes A_0, A_1 and A_2 are

connected respectively to impedances 50, 52 and 54, each of which comprises on the one hand a resonant circuit formed by an inductor and a capacitor connected in parallel and on the other hand a resistive ring. Briefly, the electrodes are made of longitudinal strips connected to each other by a small resistance in order to form a resistive ring having a small resistance (0.5 Ω) for the currents at the first and second frequencies. The resistive ring provides a noticeable resistance (5 Ω) for the currents induced at the third frequency. The resistive ring and the resonant circuit as combined form a selective composite impedance having a value which is low (about .5 Ω) at the first and the second frequencies (280 Hz and 35 Hz) respectively used for the shallow and the deep resistivity measurements and which is much higher (about 1.000 Ω) at the third frequency (20 KHz) used for the induction measurements. A more detailed description is provided below in connection with Fig. 6.

Two terminals 56 and 58 of an adjustable current source 60 operating at the first frequency (280 Hz) are respectively connected to one end of the impedances 50 and 52, the other terminals 57 and 59 of the impedances are respectively connected to electrodes A_2 and A_1. A tuned monitoring amplifier 62 having a gain G at the first frequency and a minimal gain at other frequencies, has two input terminals respectively connected to monitoring electrodes M_1 and M_2 and two output terminals connected to terminals 56 and 53 of impedances 50 and 54 respectively. The other terminal 55 of impedance 54 is connected to electrode A_0.

In the configuration of Fig. 3A, the focusing current I_{A1} is supplied by current source 60 through electrode A_1 and is received at electrode A_2. Survey or measure current I_{OS} is emitted from electrode A_0 and collected at electrode A_2. The intensity and phase of current I_{OS} are controlled through monitoring amplifier 62 to keep voltages V_{M1} and V_{M2} of monitoring electrodes M_1 and M_2 at substantially the same value. Additionally, the intensity of focusing current I_{A1} is controlled so as to keep substantially constant the product of the measure voltage V_{M1} of electrode M_1 (taken vis-a-vis the reference electrode 41) and the measure curent I_{OS}. A drawback of the circuit of Fig. 3A stems from the fact that impedance 50 is traversed by a current $(I_{OS}+I_{A1})$, where the intensity of the focusing current I_{A1} is generally 100 or 1,000 times higher than the intensity of the measure current I_{OS}. As a consequence, an important drop of potential occurs in impedance 50. This spurious drop of potential has to be compensated for by monitoring amplifier 62 and therefore its gain G has to be high leading to loop instability. According to the present invention the circuit represented in Fig. 3C has been designed and implemented to prevent such loop instability. The circuit of Fig. 3B is provided as an intermediate step toward the actual circuit of the invention shown in Fig. 3C.

In Fig. 3B, the output terminal of amplifier 62 previously connected to terminal 56 of current source 60, is connected to the other terminal 58 of source 60. Thusly, the measure current I_{OS} is received at electrode A_1 instead of at electrode A_2. If I_{A1} still designates the focusing current flowing through impedance 52 and electrode A_1, then the intensity of the measure current circulating in the loop 53 is $I_{OS}$and that of the total current circulating in the loop 51 is $(I_{A1}+I_{OS})$. It can be noticed that monitoring amplifier 62 still has to overcome a high drop of potential in impedance 52 through which flows current I_{A1}.

It can be demonstrated by applying the principle of superposition that the circuit of Fig. 3B works as if survey or measure current I_{OS} were received at electrode A_2. Another way of understanding the equivalence of the circuits of Fig. 3A and 3B, is to look at the influence of the currents emitted or received by each electrode on the resistivity measurement, therefore on the potential of monitoring electrodes M_1 and M_2. The measure current emitted by electrode A_0 is $+I_{OS}$ in both circuits. Focusing currents flowing from electrode A_1 is I_{A1} for the circuit of Fig. 3A and

$$+(I_{A1}+I_{OS})-I_{OS}=+I_{A1}$$

for the circuit of Fig. 3B. As far as electrode A_2 is concerned the total current flow is $-(I_{OS}+I_{A1})$ in both cases. The value and the sign (for direction of flow) of the current of each electrode being the same in both circuits, these circuits are equivalent.

The circuit represented in Fig. 3C is identical to the one of Fig. 3B except that instead of having one selective impedance 52 connected between electrode A_1 and terminal 58, it comprises, in accordance with principles the present invention, two independent selective circuits connected in parallel to electrode A_1. Impedance 64, connected between electrode A_1 and the output terminal of amplifier 62, provides a path for current I_{OS} while impedance 66, connected between the current source 60 and electrode A_1, provides a path for current $(I_{A1}+I_{OS})$. It will be appreciated that loop 53 formed by electrode A_1, impedance 64, amplifier 62, impedance 54, electrode A_0 and the formation provides a flow path for the current I_{OS}. Similarly, loop 61 formed by electrodes A_1, A_2, impedance 50, current source 60, the formation and impedance 66 provides a flow path for current $(I_{A1}+I_{OS})$.

Keeping in mind the fact that the intensity of focusing current I_{A1} is several hundred times larger than the intensity of measure current I_{OS}, one realizes that the high spurious drop of potential across impedance 64 no longer exists and that the gain G of monitoring amplifier 62 does not have to be inordinantly large to compensate therefor. The two separate flow paths for the connections to the electrode A_1 effect a suppression of the adverse coupling between the measure current I_{OS} produced by monitoring amplifier 62, and the focusing current produced by current source 60.

Fig. 4 represents one-half of the electrode array of Fig. 1, when its associated circuits for deep investigation of the earth formations. A current source 68 supplies a current I_2 between the remote return electrode B located at the surface and the sonde current electedes A_0, A_1 and A_2. Electrode M_3 is connected to one of two input terminals of another tuned monitoring amplifier 74 having a gain G at the second frequency (35 Hz) and a minimal gain at other frequencies. Another input terminal of amplifier 74 is connected to electrode M_1. In association with the above circuits, a compensation device is used which comprises: two current transformers 70—71 and an amplifier 72 tuned to the deep investigation frequency. A primary winding 80 of transformer 70 is connected between terminal 63 of impedance 64 and one output terminal of amplifier 74 while a primary winding 82 of transformer 71 is connected between terminal 58 of impedance 66 and one output terminal of amplifier 72, the other output terminal of the amplifier 72 is connected to terminal 56 of impedance 50. The secondary windings 84 and 86 of transformers 70 and 71 are respectively connected in series and in phase opposition to the input terminals of amplifier 72.

In the theoretical working of the electrode array for a deep investigation of the earth formations, total current (the measure current I_{OD} plus the focusing current) is supplied by current source 68 and emitted into the formations. The measure current I_{OD}, is emitted from electrode A_0 and returned to the surface and the intensity of current I_{OD} is controlled by monitoring amplifier 74 so as to keep the voltages V_{M1} and V_{M3} of electrodes M_1 and M_3 at substantially the same value. Furthermore, the total current supplied by source 68 is advantageously adjusted so as to keep approximately constant the value of the electrical power $I_{OD} \cdot V_{M1}$.

In the practical implementation shown in Fig. 4, the measure current I_{OD} is virtually returned at electrode A_1 and an auxiliary current I'_{A1} is emitted from electrode A_1 and collected at electrode A_2. Because of the principle of superposition it can be demonstrated that, for sufficiently high gains of monitoring amplifier 74 and amplifier 72, the theoretical configuration (not shown) and the practical configuration (Fig. 4) are practically equivalent. One can see that the deep investigation current I_{OD} is emitted by electrode A_0 and a current I'_{A1} flows through impedance 66 and is emitted from electrode A_1. Therefore, the focusing current emitted by electrode A_2 towards the surface is $(I_2 - I'_{A1})$.

In the deep invetigation mode, electrode A_1 should not transmit any current (at 35 Hz) into the formations. To comply with this requirement the auxiliary current I'_{A1} emitted by electrode A1 has to be substantially equal to current I_{OD} received by electrode A_1. To this end the secondary windings of transformers 70—71 compare the measure current I_{OD} flowing in winding 80 and impedance 66. The secondary windings 84 and 86 of transformers 70—71 are connected in phase opposition as so, they feed the inputs of amplifier 72 with a voltage which is proportional to the difference between I'_{A1} and I_{OD}. Amplifier 72 then keeps the auxiliary current I_{A1} equal to and of opposite sign to measure current I_{OD} so that the net current coming out of electrode A_1 is practically nil.

In Fig. 5, there is represented one-half of an electrode system in accordance with the present invention and suitable for a dual mode of investigation which system results from a combination of the shallow investigation circuit represented in Fig. 3C, and the deep investigation circuit of Fig. 4. In this system electrode A_2 is connected to the second current (35 Hz) source 68 through impedance 50. A reference signal, representative of the first (280 Hz) current supplied by source 60, is applied to terminal 73 which is connected to one input of a summing element 78, e.g. an operation amplifier, another input of the element 78 being connected to the output of amplifier 72. The output of summing element 78 is connected to one output of a unity gain amplifier 90 whose other input is linked to a ground terminal. Two outputs of amplifier 90 are respectively connected to terminal 56 and to winding 82. Electrode A_1 is connected to windings 80 and 82 through respective impedances 64 and 66. Monitoring electrodes (M_1, M_2) and (M_1, M_3) are connected respectively to inputs of amplifiers 62 and 74, and the outputs of these amplifiers are, in turn, connected to the inputs of a summing circuit 92, e.g. an operationa amplifier. The output of circuit 92 is connected to one input of a unity gain amplifier 76, while another input of the amplifier is grounded. Outputs of amplifier 76 are respectively connected to the primary winding 80 of transformer 70 and to impedance 54.

Functionally, the circuit of Fig. 5 operates as explained previously with regard to operation in shallow and deep investigation modes of the systems of Figs. 3C and 4 respectively and will therefore not be further discussed.

Fig. 6 represents the two selective composite impedances 64 and 66 associated with the auxiliary current electrode A_1 in the system of Fig. 5. Electrode A_1 is made up of six metal strips 101—106, placed on a flexible support (not shown). The impedances 64 and 66, are identical and each includes respective circuits 107 and 108 formed by the parallel connection of induction coils 109, 110, with respective capacitors 111, 112, in series with respective rings 113, 114.

Ring 113 is formed by the anti-clockwise serial connections of resistors 117a, 123a, 129a, 133, 129b, 123b and 117b each having the following respective values r/3, 2r/3, 2r/3, 2r, 2r/3, 2r/3 and r/3 (i.e. r=1 Ω). Strips 103, 106 are connected directly to the ring while strips 101, 102, 104 and 105 are coupled to the ring through respective impedances 121a, 127a, 127b and 121b having

the following respective values 2r, 2r/3, 2r/3 and 2r. One terminal of capacitor 111 is coupled to the junction 115 of resistors 117a and 117b while strips 101—106 are coupled to the subsequent ring resistor junctions as one proceeds along the ring in an anti-clockwise direction.

Ring 114 is similar to ring 113 being coupled to opposite ends of strips 101—106. Reference numerals of ring 113 when incremented by one yield the elements of ring 114.

During logging operations strip-electrodes 101 to 106 are in contact with drilling mud and are thus at the same potential. Consequently, if one assumes that the inherent resistance of the strip-electrodes is negligible, terminal 115 is coupled to the mud through two parallel resistances each having a value r for a total resistance valve of r/2. It will be noted that resistor 133 does not play any role in the current supply of the strip electrodes 101—106. In fact, as the strip-electrodes 103 and 106 are effectively connected through the mud, the function of the resistor 133 is basically to stabilize this connection and to present higher impedance for any induced high-frequency currents. With such resistive rings, the currents at the first and second frequency applied to the current electrodes are distributed equally between each of the six metal strips making up these electrodes.

A selective composite impedance (resonant circuit and resistive ring) identical to those described with reference to impedance 64 of Fig. 6 is placed in series with each of the other current electrodes of the electrode system of Figs. 2 to 5.

While there have been described what are presently considered to be preferred embodiments of this invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the principles of the present invention which covers all such changes and modifications as fall within the true spirit and scope of the invention.

Claims

1. A well logging method for measuring the electrical resistivity of two underground formation zones respectively near and far from a borehole, comprising the following steps:
—applying at a first location of the borehole and receiving at two second locations of the borehole symmetrically situated on both sides of said first location along the borehole axis, a first measurement current at a first frequency,
—applying at two third locations of the borehole symmetrically situated on both sides of said first location along the borehole axis, between said second locations, and receiving at said second locations, a first focusing current at said first frequency,
—varying the amplitude of said first measurement current so as to minimize the potential difference existing at the first frequency between respective ones of two fourth and two fifth locations symmetrically situated along the borehole axis on both sides of said first location, between said two third locations,
—deriving a measure of the resistivity of a formation zone which is near the borehole from the amplitude of said first measurement current and from the potential difference existing at the first frequency between said two fourth locations and a sixth location along the borehole axis a very large distance from said first location,
—applying at said first location and receiving at a seventh location on the surface, a second measurement current at a second frequency,
—applying at said second locations and receiving at said seventh locations a second focusing current at said second frequency,
—varying the amplitude of the second measurement current so as to minimize the potential difference existing at said second frequency between said two fourth locations and two eighth locations respectively situated symmetrically on both sides of said first location between said third and fifth locations, and
—deriving a measure of the resistivity of said zone far from the borehole from the amplitude of said second measurement current and from the potential difference existing at the second frequency between said fourth locations and said sixth location, wherein
—said two second locations respectively extend along the borehole axis in a longitudinal dimension which is small relative to their spacing along the axis,
—said eighth locations is positioned midway between said third and fifth locations, and
—the amplitude of said second measurement current flowing, at said second frequency, in said third locations is minimized.

2. A well logging method in accordance with Claim 1, comprising the following additional steps:
—inducing into the formation zones electromagnetic energy at a third frequency considerably higher than said first and second frequencies,
—deriving a measure of the currents at the third frequency induced in the formation zones and deriving therefrom a value for the conductivity of these formation zones,
—modifying the flow conditions of the focusing and measurement currents at said first and second frequencies at said two third locations such that two independent flow paths are respectively provided for said focusing currents and said measurement currents.

3. Well logging sonde for simultaneously measuring the values of the resistivity of two underground formation zones located respectively near and far from a borehole, comprising:
—an elongated support member, and
—a plurality of electrodes supported on said member so as to be longitudinally spaced apart, and including:
—a central current electrode, a first, second and third pairs of auxiliary voltage electrodes, a first

and a second pair of auxiliary current electrodes, each of said pairs of auxiliary electrodes being symmetrically arranged in relation to said central electrode, respective ones of said second pair of auxiliary current electrodes being farther from the central electrode than respective ones of said first pair of auxiliary current electrodes, and the first and second pairs of auxiliary voltage electrodes being respectively arranged between the central electrode and the first pair of auxiliary current electrodes, wherein:

—the dimension of the electrodes of the second pair of auxiliary current electrodes along the axis of the support member is small relative to their spacing along the support member and — said third pair of auxiliary voltage electrodes is supported midway between respective ones of the second pair of auxiliary voltage electrodes and the first pair of auxiliary current electrodes.

4. Well logging apparatus for measuring the electrical resistivities to two underground formation zones respectively near and far from a borehole, comprising:

—a surface apparatus, a cable and an elongated sonde supported in the borehole by said cable, said sonde being equipped with a central current electrode, a first and a sedond pair of auxiliary voltage electrodes, and a first and second pair of auxiliary current electrodes, each of said pairs of auxiliary electrodes being respectively arranged along the length of the sonde symmetrically in relation to said central electrode, said second pair of auxiliary current electrodes being farther from the central electrode than said first pair of auxiliary current electrodes, said first and second pairs of auxiliary voltage electrodes being respectively arranged between said central electrode and said first pair of auxiliary current electrodes, a reference voltage electrode is supported on an insulated section of said cable, at a large distance from said sonde, and a distant current return electrode, located in the formations at a great distance from said sonde,

—a first measurement current source at a first frequency, coupled between said central electrode and said second pair of auxiliary current electrodes,

—a first focusing current source at said first frequency, coupled between said first pair of auxiliary current electrodes and said second pair of auxiliary electrodes,

—means for measuring, in relation to said reference electrode, the potentials existing at said first frequency at said first and second pairs of auxilairy voltage electrodes,

—a first feedback loop for minimizing the potential difference existing at said first frequency between said first and second pairs of auxiliary voltage electrodes, by varying the amplitude of said first measurement current,

—means for deriving a measure of the resistivity of the near formation zones surrounding said borehole, from the amplitude of one of said potentials at said first frequency and the intensity of said first measurement current,

—a second measurement current source at a second frequency effectively coupled between said central electrode and said distant current return electrode, wherein

—a second focusing current source at said second frequency coupled between said second pair of auxiliary current electrodes and said distant current return electrode,

—means for measuring, in relation to said reference electrode, the potential at said second frequency at said first pair of auxiliary voltage electrodes and at another pair of auxiliary voltage electrodes supported on the sonde between said first pair of auxiliary current electrodes,

—a second feedback loop for minimizing the potential difference existing at said second frequency between said first pair of auxiliary voltage electrodes and said other pair of auxiliary voltage electrodes by varying the amplitude of said second measurement current,

—means for deriving a measure of the resistivity of the far formation zones surrounding said borehole from the amplitude of one of the potentials at said second frequency measured on one of said pairs of auxiliary voltage electrodes and the intensity of said second measurement current thus obtained, wherein the dimension along the axis of said sonde of the electrodes of said second pair of auxiliary current electrodes is very small relative to their spacing distance,

—said other pair of auxiliary voltage electrodes is a third pair of auxiliary voltage electrodes located on the sonde midway between the electrodes of said first pair of auxilairy current electrodes and those of said second pair of auxiliary voltage electrodes,

—said second measurement current source at said second frequency is coupled between said central electrode and said first pair of auxiliary current electrodes,

—an auxiliary feedback loop is provided for generating an auxiliary current at said second frequency with an amplitude equal to the amplitude of said second measurement current, said loop being coupled, between said first pair of auxiliary current electrodes and said second pair of auxiliary current electrodes.

5. Well logging apparatus according to Claim 4, further comprising:

—means for inducing into the formation zones electromagnetic energy at a third frequency much higher than said first and second frequencies,

—means for measuring the amplitude of the currents at said third frequency induced in said formation zones, wherein

—each of said electrodes includes longitudinal conducting strips coupled by a resistive ring, coupled in series with a resonant circuit constituting both a high impedance circuit for the currents at said third frequency and a relatively low impedance circuit for said currents at the first and second frequencies, and

—said electrodes of said first pair of auxiliary current electgodes being coupled to said first focusing current source and said first

measurement current source through respectively separate resistive rings and resonant circuits.

6. An apparatus for the electrical investigations of earth formations traversed by a borehole, comprising:
—an elongated support member,
—a plurality of electrodes supported in spaced apart relationship along the length of said support member, including:
—a central electrode,
—two pairs of electrodes each symmetrically positioned about said central electrode,
—a first source of electrical current coupled between said two pairs of electrodes,
—a second source of electrical current coupled between said central electrode and the one pair of electrodes of said two pairs of electrodes which is positioned nearest said central electrode, and
—electrical impedance means respectively interposed in the electrical paths between each of said first and second sources of electrical current and said one pair of electrodes.

7. The apparatus of Claim 6, wherein:
—said plurality of electrodes further comprises a second two pairs of electrodes symmetrically positioned about said central electrode between said central electrode and said one pair of electrodes, and wherein said apparatus further comprises:
—means for controlling said second source of current in accordance with the potential difference between said second two pairs of electrodes.

8. The apparatus of Claim 6, wherein:
—each of said one pair of electrodes comprises a plurality of conductive strips supported about a circumference of the support member, and wherein each of said impedance elements comprises a plurality of resistive impedances coupled to form a resistive ring through which said conductive strips are connected the one to the other, and a resonant circuit formed by the parallel connections of an inductive and a capacative impedances, said resonant circuit being serially coupled with said resistive ring.

9. An apparatus for the electrical investigation of earth formations traversed by a borehole, comprising:
—an elongate support member,
—a plurality of electrodes supported in spaced apart relationship along the length of said support member, including:
—a central electrode,
—two pairs of electrodes each symmetrically positioned about said central electrode,
—a first source of electrical current coupled between said two pairs of electrodes,
—a second source of electrical current coupled between said central electrode and the one pair of electrodes of said two pairs of electrodes which is positioned nearest said central electrode,
—first and second electrical impedance means respectively interposed in the electrical paths between each of said first and second sources of electrical current and said one pair of electrodes, and
—means for controlling the output of said first source of current so as to provide a current flow through said first impedance means which is equal in magnitude and opposite in direction to the current flow through said second impedance means.

10. The apparatus of Claim 9, wherein:
—said plurality of electrodes further comprises a second two pairs of electrodes symmetrically positioned about said central electrode between said central electrode and said one pair of electrodes and wherein said apparatus further comprises:
—means for controlling the output of said second source of current in accordance with the potential difference between said second two pairs of electrodes.

11. An apparatus for the investigation of earth formations traversed by a borehole, comprising:
—an elongated support member,
—a plurality of electrodes supported in spaced apart relationship along the length of said support member, including:
—a central electrode,
—two pairs of electrodes each symmetrically positioned about said central electrode,
—a first source of electrical current at a first and second frequencies, coupled between said two pairs of electrodes,
—a second source of electrical current at said first and second frequencies, coupled between said central electrode and the one pair of electrodes of said two pairs of electrodes which are positioned nearest said central electrode;
—first and second electrical impedance means respectively interposed in the electrical paths between each of said first and second sources of electrical current and said one pair of electrodes, and,
—means for controlling the output of said first source of current so as to provide a current flow at said first frequency through said first impedance means which is equal in magnitude and opposite in direction to the current flow at said first frequency through said second impedance means.

12. The apparatus of Claim 11, wherein:
—said plurality of electrodes further comprises a second two pairs of electrodes symmetrically positioned about said central electrode between said central electrode and said one pair of electrodes, and wherein said apparatus further comprises:
—means for controlling the output of said second source of current at said second frequency in accordance with the potential difference between said second two pairs of electrodes.

13. The apparatus of Claim 12, wherein:
—said plurality of electrodes further comprises an additional pair of electrodes symmetrically positioned about said central electrode between said second two pairs of electrodes and said one pair of electrodes, and wherein said apparatus further comprises:

—means for controlling the output of said second source of current at said first frequency in accordance with the potential difference between said additional pair of electrodes and the one pair of electrodes of said second pair of electrodes nearest said central electrode.

14. The apparatus of Claim 13, wherein:
—each of said additional electrodes is positioned on said support member midway between the aforementioned electrodes adjacent thereto.

15. The apparatus of Claim 11, wherein:
—said plurality of electrodes further comprises a second two pairs of electrodes symmetrically positioned about said central electrode between said central electrode and said one pair of electrodes, and wherein said apparatus further comprises:
—means for controlling the output of said second source of current at said first frequency in accordance with the potential difference between said second two pairs of electrodes.

16. The apparatus of Claims 11, 12, 13, 14, or 15, further comprising:
—means, supported by said support member, for inducing at a third frequency electromagnetic energy, wherein the length, along the axis of the support member, of each of the electrodes of the pair of electrodes of said first mentioned two pairs of electrodes which are positioned farthest from said central electrode, is several orders of magnitude smaller than the relative spacing along the support member of said respective pair of electrodes.

17. The apparatus of Claim 16 further comprising:
—means, including an electrode mounted on said support member, for measuring the spontaneous potential of the earth formations traversed.

18. The apparatus of Claim 17 further comprising:
—means for detecting the induced electromagnetic energy,
—means for detecting the output current of said central electrode,
—means for detecting the electrical potential generated at said plurality of electrodes, and
—means adapted to receive the outputs of said detecting means and said spontaneous potential measuring means for the recording thereof as a function of borehole depth.

19. An apparatus for the electrical investigation of earth formation traversed by a borehole, comprising:
—an elongated support member,
—an electrode system, supported on said support member, comprising a central electrode and five pairs of electrodes respectively short-circuited and aligned symmetrically about said central electrode at increasing distances therefrom, the central electrode and the electrodes of the fourth and fifth pairs being called current electrodes, the electrodes of the first, second and third pairs being called voltage electrodes;
—means for producing an alternating current at a first frequency, f_1, coupled between the electrodes of the fifth and fourth pairs,
—means for producing an alternating current at a second frequency, f_2, coupled between the electrodes of the fifth pair and an electrode at electrical infinity with respect to the electrode system;
—means, coupled between the electrodes of said central electrodes and of said fourth pair, for (1) maintaining the potential difference between the first and second pairs of electrodes at substantially zero, said means adapted to monitor the potential difference between the first and second pairs of electrodes and to emit current at said first frequency from the central current emitting electrode in response to the measured potential difference to reduce the potential difference to zero, and for (2) maintaining the potential difference between the first and third pairs of electrodes at substantially zero, said means adapted to monitor the potential difference between the first and third pairs of electrodes and to emit current at said second frequency from the central current emitting electrode in response to the measured potential difference to reduce the potential difference to zero, and
—first and second means, respectively interposed between each of said current producing means and said maintaining means and the fourth pair of current electrodes for providing electrical impedance to the flow of current therethrough.

20. The apparatus of Claim 19 further comprising:
—means for measuring the electrical potential proximate to one of the first, second and third pair of electrodes and the current emitted from the central electrode at said two frequencies to produce therefrom signals representative of the electrical resisitivity of the formation located at different lateral distances from the borehole, and
—means for providing a record of the output of said measuring means as a function of borehole depth.

21. The apparatus of Claim 19 wherein said means for producing an alternating current at frequency f_2 is coupled between the fifth pair of current electrodes and the electrode at electrical infinity.

22. The apparatus of Claims 19, 20 or 21, further comprising:
—means, supported on said support member, for inducing at third frequency f_3 electromagnetic energy, wherein:
—the length, along the axis of the support member, of each of the electrodes of the fifth pair is several orders of magnitude smaller than the relative spacing along the support member of said fifth pair of electrodes.

23. The apparatus of Claim 22, further comprising:
—means, including an electrode mounted on said support member, for measuring the spontaneous potential of earth formations traversed.

24. A well logging method for measuring the electrical resistivity of two underground formation

zones respectively near and far from a borehole, the method being substantially as hereinbefore described with reference to the accompanying drawings.

25. A well logging apparatus for measuring the electrical resistivities of two underground formation zones respectively near and far from a borehole, the apparatus being substantially as hereinbefore described with reference to the accompanying drawings.

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